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Can We Hope to Make Today's Concern about Ageing Aircraft - a Thing of the Past?

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Abstract

According to Dr. Hart Smith "If the well known fuselage splice fatigue problem were removed from consideration, the remainder of the structure have performed well enough to outlast the arrival of the next generation of improved engines or systems most of the time". In other words, apart from the lap splices, technical obsolescence for the whole aircraft arrived before the airframe became too expensive to continue to operate. The paper gives a glimpse of the historical development of fuselage splice joints. Through many ups and downs in aircraft industry, design of long life splice joint has come to a mature stage. Many forgotten features of splice design of early 50's have been revived. To extend the fatigue life considerably, new features have been incorporated. Some of the intricacies of fuselage splices are discussed in detail in this paper.

Keywords: Fatigue, Fuselage, Splice joint, Rivets, Cold working.

1. Introduction

As the aircraft ages the cost of maintenance, through inspection and repair/replacement, increases rapidly. At a certain point in service life it becomes no longer possible to continue it as a passenger aircraft. It gets converted to a freighter and continues in service. Further down the line it becomes uneconomical to operate the aircraft (due to maintenance cost). And that is the end of the aircraft's economic life.

In essence, the aircraft ageing is a "durability" issue. Fatigue cracks are to be spotted and repaired. Multi-site-damage and widespread-fatigue damage appear primarily in the skin splice joints of the fuselage due to pressure cycling. In spite of the best efforts of the designer, fuselage splice fatigue cracks appear even during the initial design fatigue life. In fact, if the fatigue cracking problem of fuselage splice joints are taken out of consideration, then technological obsolescence of the aircraft systems will arrive early compared to the ageing problems of the remainder structure of the airframe [1]. The key to the ageing transport aircraft problem therefore lies in the fuselage splice joints.

2. Design of Splice Joints

The static strength design of any joint assumes that there is sufficient yielding to create a uniform state of stress in every net section before failure. This is the traditional fully-plastic design concept. The load transfer (ultimate) through the joint is calculated based on this fully plastic deformation. In essence the stress concentration effect disappears.

Now consider the state of stress under the condition of fatigue loading during the normal operating conditions. The load levels are much lower. The stress concentration leads to large stress gradients in every net section. At the locations of fatigue cracking, fatigue damage accumulates under high local stress levels. Therefore, the geometric proportion needed to maximize ultimate load carrying capacity is not the same as that required for long fatigue life.

Let us look at the stress distribution around a pin-loaded hole. Bickley [2] in 1928 has provided this classical result for a pin-loaded hole in an infinite plate. This is shown in Fig. 1.

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The peak hoop stress is P/dt and the peak bearing stress is $4P/\pi dt$. It is straightforward to comment that these stresses depend on the pin-load.

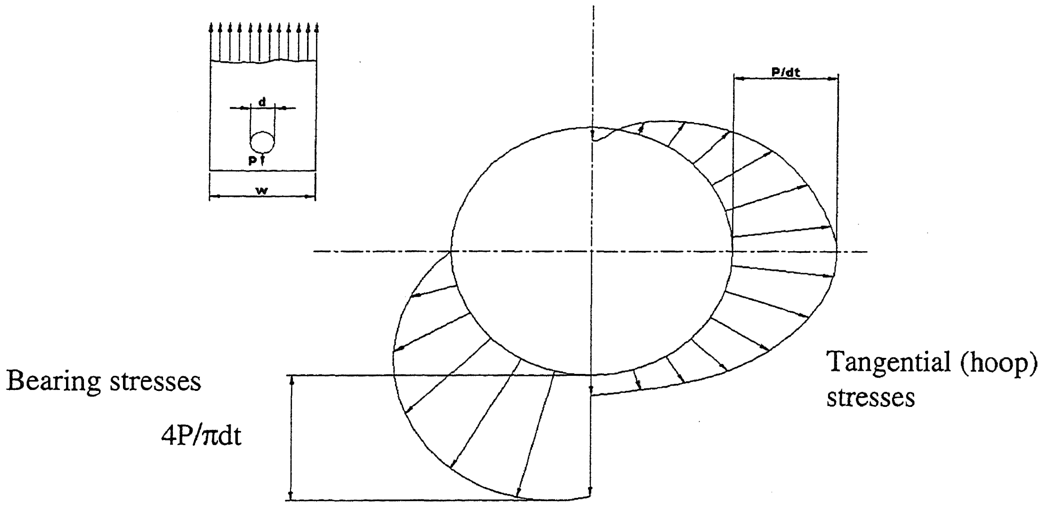

Fig. 1. The stress distribution in a pin loaded hole

In contrast, much insight into the fatigue response can be had if one sees the one-to-one relationship between the bearing stress and the hoop stress in a loaded hole. It is the hoop stress that initiates the fatigue crack. *It is noteworthy to realize that it is the bearing stress that controls the hoop stress.*

Static strength designers of the airframe believe in designing a splice joint against net section failure. For this they reduce the by-pass load by increasing the bearing load. They also believe that bearing failure being ductile will give some warning of imminent failure. While this concept works for a pristine airframe it is unable to retain the desired residual strength.

Believing on this design concept, sometime in early 70's the soft 2000 series rivets were replaced by stronger 7000 series rivets in order to reduce the rivet size. This led to an increase in bearing stress and a decrease in net stress. Consequence was widespread cracking problem in service. Once a crack starts from a rivet hole the net section decreases, thereby, increasing the net stress. This defeats the very purpose for which stronger rivets were used in the first place.

There appears to be a conflict of interest between the requirements for i) high static strength ii) long fatigue life (high residual strength). This conflict can amicably be resolved through the use of larger diameter softer rivets. The larger diameter rivets will increase the rivet load and reduce the by-pass load. At the same time it will also not increase the bearing stress (due to the increase in diameter).

A thorough understanding of the interrelationship between the bearing stress and hoop tensile stress is required to develop efficient joints. This is depicted in Fig. 2. This figure plots the ratio of gross-section stress to peak hoop stress as a function of d/w for various values of the bearing stress. In order to increase the static load carrying capacity we need to maximize the gross section stress. Further the peak hoop stress should be a minimum for the highest possible fatigue life. Both of these objectives are achieved by looking for the highest value of the y-coordinate in this figure.

For example, for a single row bolted joint there is no by-pass load. The peak hoop stress is minimum for $d/w \cong 4$ and for any other value the peak hoop stress is higher. Therefore selection of $d/w = 0.4$ will maximize fatigue life. For the single row joint the bearing stress is 100%. As the σ_{bearing} decreases the d/w required to maximize fatigue life decreases. Therefore, in a multi-row joint one should select the d/w in various rows depending on the bearing load. A careful selection of rivets and rivet hole parameters to achieve the highest overall efficiency of the joint is required. Another tool available to the airframe designer to improve fatigue life of fastened joints is the "cold working" of the holes. Cold working when done with understanding creates favorable compressive hoop stresses around the hole.

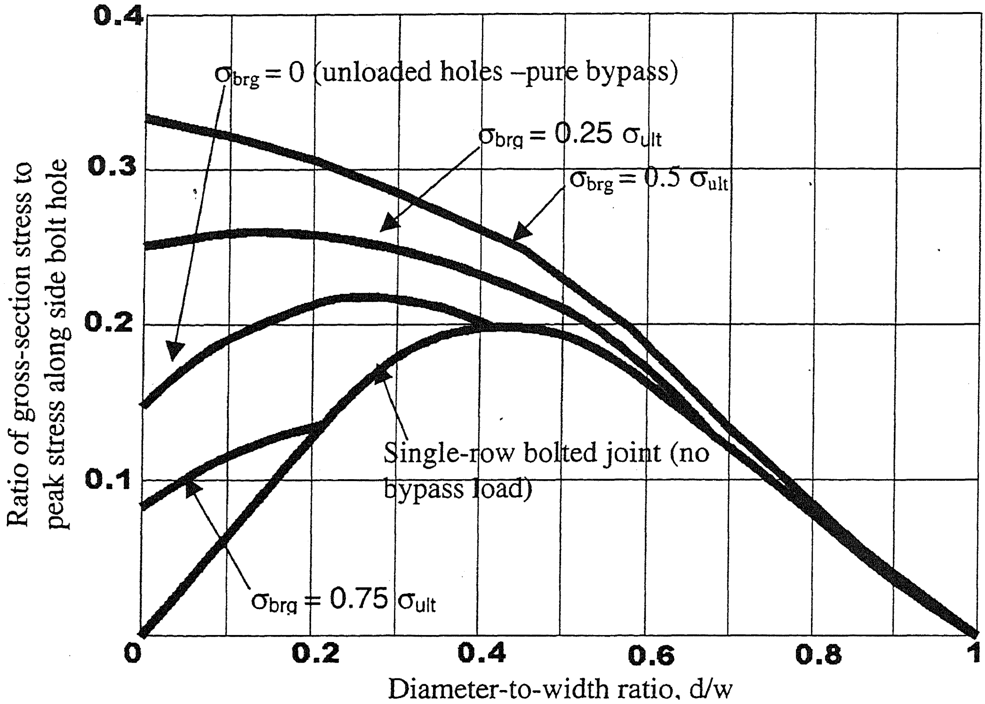

Fig. 2. Variation of ratio of gross stress to peak stress with d/w as a function of bearing stress.

3. Doing "Cold Working" with Understanding

An oversized mandrel is used to cold work holes in a pin and / or bolted joint. This process expands the hole. The material surrounding the hole first expands elastically and then deforms plastically. This expansion leads to a tensile stress in the circumferential direction (hoop stress) and a compressive stress in the radial direction so long as the mandrel is in place. Once the mandrel is removed, the region surrounding the plastically deformed ring of material around the hole, which has deformed only elastically, tries to come back to its original location. In this process it compresses the plastically deformed material making the expanded hole shrink a bit. With this shrinking, the material surrounding the hole now has compressive stress in both circumferential and radial directions. The hole as been cold worked. A clearance fit pin or bolt can now be used in the hole to transfer the load.

Interestingly in a riveted joint this cold working has to be achieved during the process of rivet installation. Normally an undersized rivet is driven through an oversized hole through the riveting process. The rivet diameter expansion fills the hole first. Upon further expansion it must plastically deform the hole like a mandrel. When the riveting process stops the following things can happen.

1) If it is a hard rivet, it would have been able to expand under the action of riveting force. But once this force is removed, the hard rivet may not allow the shrinkage of the hole (as mentioned earlier) so *crucial* for the development of compressive hoop stress. We now have a cold worked hole with detrimental tensile hoop stress. This has been the reason for widespread cracking when 7000 series of rivets were used to increase the bearing stress mentioned earlier.
2) If the rivet is soft enough, the elastic material surrounding the plastically expanded material round the hole will be able to squeeze the rivet. The rivet diameter reduces a bit allowing the hole to shrink and the rivet increases its length a bit.

This final shrinkage of the rivet hole is *absolutely essential* for cold working of fastener holes. Therefore the rivets must be soft during installation. Even while using soft rivets, the amount of hole filing and cold working depends on whether the rivets are fine grained or coarse grained, whether the riveting process is displacement controlled or force controlled.

Many a times the displacement controlled riveting does not provide reproducible results. This is not a desirable feature from the fatigue cracking point of view. Displacement controlled riveting is sensitive to variations in hole clearances and frequently leads to unfilled holes.

In contrast, the force controlled riveting keeps squeezing the rivet till everything is bottomed out. Therefore minor variations in hole diameter and rivet size get easily accommodated in this process. Even in force controlled riveting, reproducible results can only be achieved through the use of fine grained "ice-box" rivets.

With this understanding of riveting process we may not still achieve the desired long crack free life. The rivet installation process should be able to put compressive stresses at the crack initiation location in the rivet hole and not at other places.

4. Countersunk Rivet vs. NACA Rivet Installation

In all aerodynamic surfaces countersunk rivets are used. Figure 3 shows the installation process of a countersunk rivet. The outer skin has a countersunk hole. The rivet is installed from outside. The rivet has a countersunk head. As the rivet is squeezed, the head is formed on the inside skin.

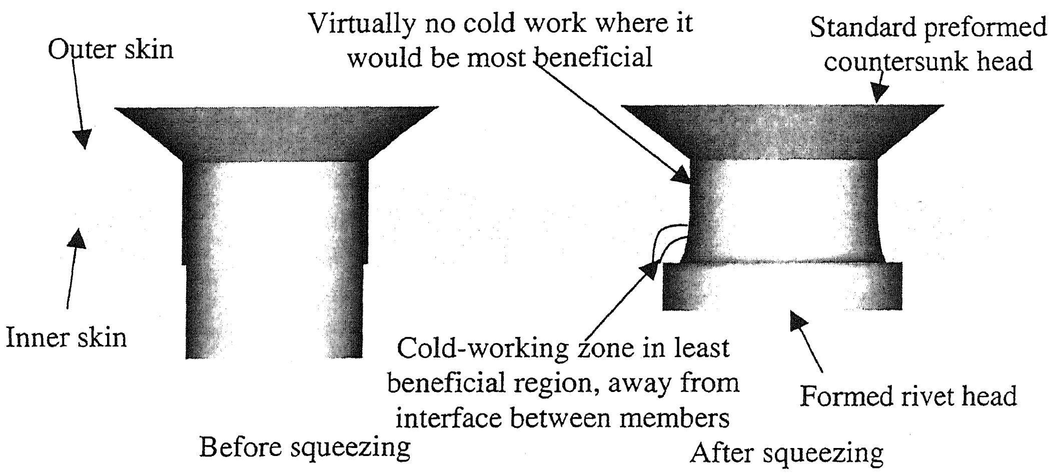

Fig. 3. A schematic of standard rivet installation process

The stages of rivet expansion and cold working of the skin are also depicted in this figure. As can be seen in this figure, the effective cold working is on the outer edge of the inner skin rivet hole. Unfortunately, there is hardly any cold working near the interface of the two skins where fatigue cracks initiate.

Let us now compare this with NACA rivet installation which is shown in Fig. 4. The outer skin hole is countersunk. The rivet does not have a preformed countersunk head. The rivet is installed from inside out. The countersunk head is formed during riveting. The deformed shape of the rivet is shown in the figure. As can be seen, cold working is achieved exactly where it is most needed. The rivet head is formed on the inside. This riveting process fills the countersunk recess of the outer skin so well that corrosion is practically eliminated. In order to get a smooth surface the protruding tail of the rivet has to be shaved off. This is one additional process needed in NACA rivet installation.

Surprisingly today NACA rivets are not in use. Interestingly enough NACA riveting was very much in vogue during world war-II when the service lives were measured in only hundreds of hours. The key features of this riveting process that are crucial for enhancing fatigue life were not fully understood at that time. As a consequence the NACA rivet installation was gradually abandoned after world war-II during the period where the demand for fatigue performance was not that much as it is today. The reason advanced for this was the additional cost involved in shaving off the protruding rivet heads.

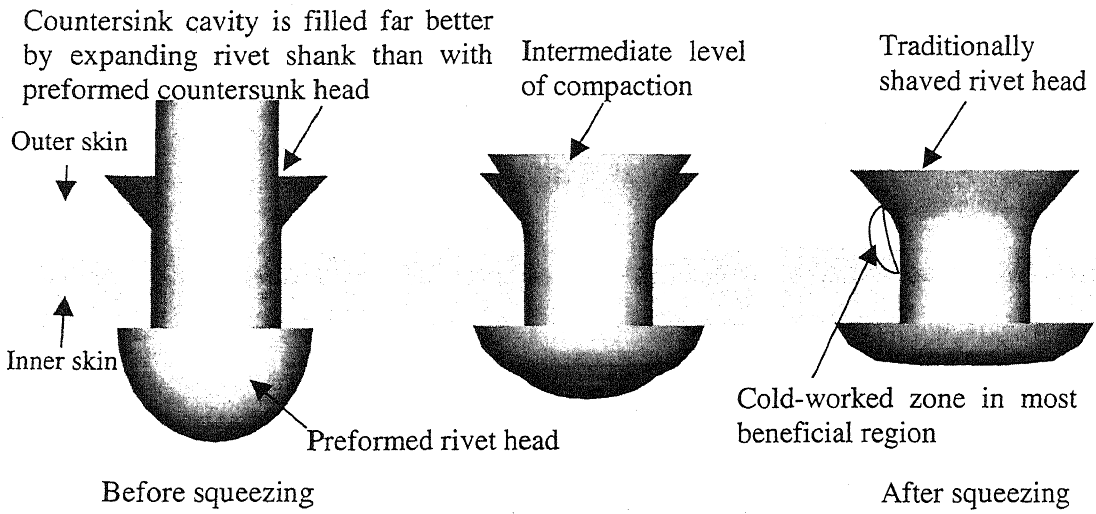

Fig. 4. NACA rivet installation process.

Fortunately some of the old timers at Douglas knew the benefits of NACA riveting when Douglas took up the design of DC-8 in 1955. A typical DC-8 longitudinal fuselage skin splice is shown in Fig. 5. The two skins are butted together smoothly. Thus there is no primary load eccentricity in the load path between the two skins. This one sided butt splice design had only two rows of rivets and all the rivets were NACA rivets.

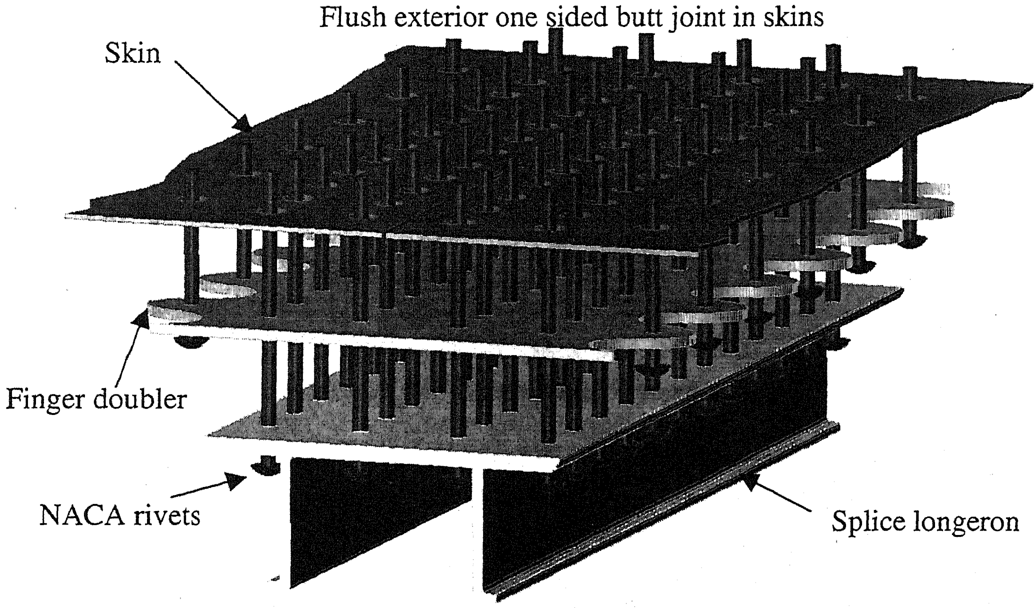

Fig. 5. Longitudinal skin butt splice on DC-8

This splice was so effective that throughout the entire service history of DC-8 not even one AD ever was issued against this splice. Many of the DC-8s are in use as freighter even to-day. Their passenger service was discontinued because their systems became obsolete long before the airframes showed any sign of age.

In Dr Hart Smith's considered opinion "the use of NACA rivet installation with ice-box rivets had much to do with DC-8's longevity". Douglas continued NACA riveting in DC-9 and DC-10 which are still flying today. These aircrafts have an enviable record in terms of airframe durability. This was a major factor in their ability to compete with the products from far larger aircraft companies. There are many additional interesting features in DC-9 and DC-10 fuselage splice joints [1] which could not be covered here.

5. The Problem of Fatigue Cracking in the Fuselage Lap Splice Joints.

Unlike a butt joint, one skin is concealed under the other in the lap joint. It is, therefore, necessary to design the lap joint in such a way that the first fatigue cracks must appear at the visible location i.e. the outer skin must crack in the first row of rivets. At the same time care should be taken to ensure that this first row rivet cracking does not lead to the problem of MSD. The other important difference between the butt and lap splices is the load path eccentricity between the two skins which creates bending of the lap joint.

Let us analyze the lap joint in some detail. Fig. 6 shows a simple analytical model of a lap joint. It is represented as an overlap zone assumed to be infinitely stiff but free to rotate to ensure compatibility with the deflections and rotations of the flexible skins of which it is an integral part. This load path eccentricity induces the bending moment and rotates the overlap zone making the bending moment maximum at the ends of the overlap. A simple linear analysis will indicate that the bending moment due to load eccentricity is

$$M^{L} = Pt/2 \tag{1}$$

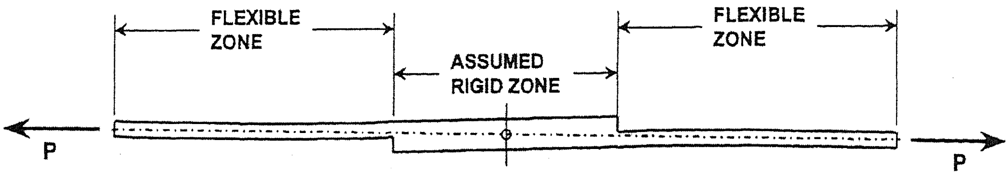

Fig. 6. Simple, but effective analysis model for designing lap splices

A geometric nonlinear analysis leads to the following expression for the bending moment at the end of the overlap:

$$M^{NL} = (Pt/2)\ \{1/(1+Gc)\} \tag{2}$$

where, $C = ½$ (overlap length), $G^2 = P/D$, $D = Et^3 / 12(1-\Upsilon^2)$ and Υ = Poisson's ratio

Since the load P can be expressed as $\sigma * t$ where σ is the remote membrane stress on the skin, Gc can be expressed as

$$Gc = (c/t)\ \{12(1-\Upsilon^2)\ (s/E)\}^{1/2} \tag{3}$$

$$M^{NL} = (Pt/2)\ [1/\langle 1+(c/t)\ \{12(1-\Upsilon^2)\ (\sigma/E)\}^{1/2}\rangle] \tag{4}$$

It shows that, apart from other parameters, the bending moment depends inversely on the overlap length (2C). More precisely it is the overlap to eccentricity ratio (c/t). *This very significant nonlinear analytical result implies that one can reduce the bending moment at the end of the overlap by increasing the overlap length "2C".*

In 50's and 60's the inverse relationship between lap-bending moment and overlap length was not known to the designer. Therefore, during the development of lap splice joint the design "driver" was "minimum weight" of the lap joint. In order to meet this design driver the overlap length was used to be minimized. With a minimum overlap, the bending moment is maximum which has led to these fatigue cracking problems in the fuselage lap splice joints over the decades.

This understanding of the effect of overlap length on lap joint bending moment and hence on fatigue life has been very successfully employed by Boeing Company in their Monocoque with Integral Shear Ties (MIST) fuselage shell development program.

The lap splice of the MIST fuselage barrel is shown in Fig. 7. The key feature of this joint is the longer than normal overlap. The ratio of distance between the outermost rows of rivets to the eccentricity in load path was a little over 50:1. This is much more than the conventional 20:1.

As can be observed from Fig.7 at the top row of rivets the inner skin thickness was reduced to decrease the rivet load. At the same time, at the bottom row of rivets the inner skin thickness was increased to increase the bending stiffness without increasing the load eccentricity. The design service objective was 75,000 pressure cycles. The MIST was tested to 375,581 cycles. There were no visible cracks. Even when the rivet holes were drilled out during tear down inspection, no cracks were even found on the hole boundaries.

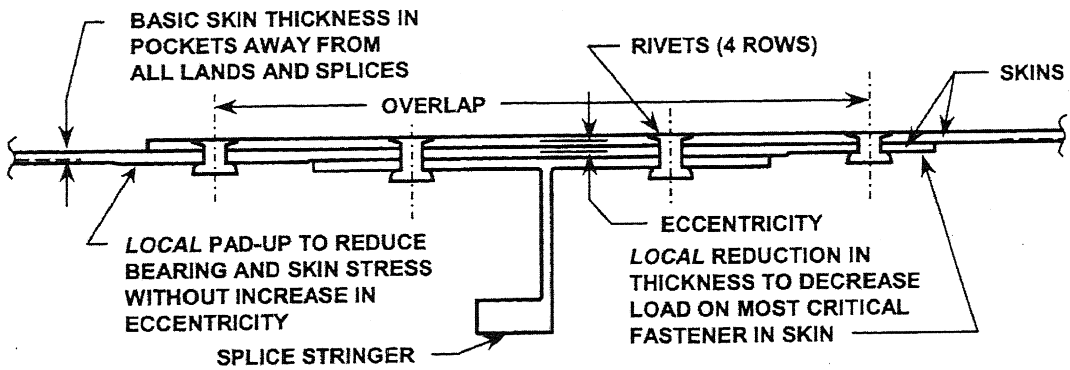

Fig. 7. Long-overlap longitudinal skin splice used on the MIST fuselage barrel.

This extraordinary fatigue performance is attributable to

1) design of the inner skin thicknesses at the top and bottom row of rivets and
2) the long overlap length.

It is also interesting to observe that instead of NACA rivets, standard Brite rivets had been used in the MIST program.

Dr Muller [3] worked in the research program to extend fatigue lives of riveted lap joints in KC-135 aircraft for USAF. He estimated that the existing KC-135 fuselage residual fatigue life can be extended to 1,000,000 pressure cycles if the existing rivets are drilled out and replaced by ice-box NACA rivets of the same diameter. Even though many rivet holes would have already suffered some fatigue damage, the cold working from the hard squeezing of NACA rivets would neutralize most such damages.

The key distinguishing differences between a butt splice and a lap splice are:

1) Load path eccentricity in the lap
2) The fatigue cracking must appear on the visible outer skin (at the first row) and not at the last row of the inner skin which is concealed under the outer skin.
3) The outer skin first row rivet hole cracks should not create MSD.

Let us examine how these issues can be addressed in a typical lap splice joint, shown in Fig. 8.

It is a short overlap joint with three rows of rivets. The left-most sketch shows conventional riveting with countersunk head rivets. This splice joint has a fatigue life of 100,000 pressure cycles and the first cracks are visible in the outer skin at the top-row of rivets. The sketch at the centre shows NACA-rivets in all three rows. The life has increased to 400,000 pressure cycles (a factor of 4). But the first cracks appear in the inner skin at the bottom row of rivets: an undesirable effect. The right-most joint uses slug rivets. Unlike the other two sketches, it has countersinking of the inner skin at the bottom row rivet holes. Even without NACA rivets the life has increasing by ten-fold. Also the first cracks appear in the outer skin at the top row of rivets.

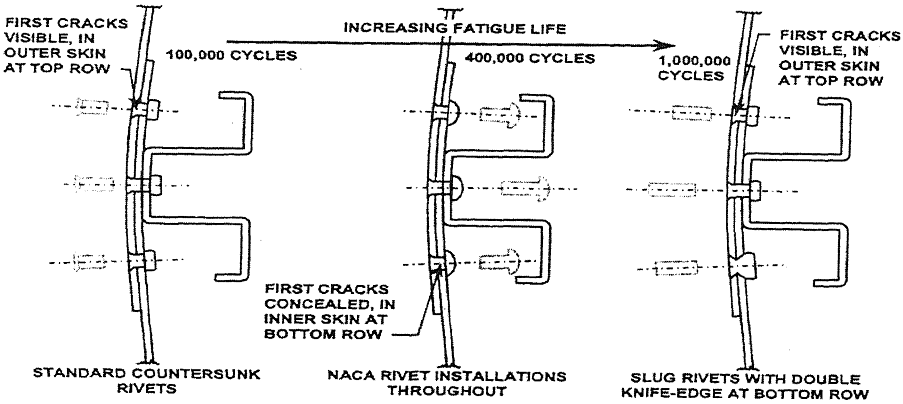

Fig. 8. Designing lap splices for very long life

Let us review the three lap joints depicted in this figure to develop a better understanding of the factors affecting the fatigue cracking. In the left-most sketch, the countersinking of the rivet holes is done on the outer skin. At the top row of rivets the bending moment is maximum on the outer skin rivet hole. It is not maximum on the inner skin rivet hole at this location. Because of countersinking only the land-area is available to take the rivet load as bearing stress on the top skin. On the other hand, the full depth of the hole (skin thickness) in the inner skin takes the same rivet load. As a consequence the rivet bearing stresses in the outer skin countersunk hole is more than that in the inner skin. Therefore, the first cracks appear in the first row of rivet holes in the outer skin.

The same conditions apply for the bottom most row of rivets. The bending moment is maximum on the bottom skin-bottom row of rivet hole location. The top skin moments are negligible. The rivet load magnitude is the same as that for the top-most row. Since the inner skin rivet holes are not countersunk, the bearing stresses are less in the inner skin. This is what that delays the fatigue cracking in the inner skin at the bottom row of rivet holes.

The bending moment on the outer skin at the top row of rivets is the same as that of the inner skin at the bottom row. Because of counter sinking recess in the outer skin, the bearing stresses in the outer skin top row rivet holes are much more than the bearing stresses in the inner skin at the bottom row of rivet holes. This explains why the fatigue cracking was observed at the top row of rivets on the outer skin.

The riveting was conventional and not NACA installation. Therefore the top row of rivets did not have the benefit of cold working. The crack initiation life was 100,000 pressure cycles. With this understanding of the left-most splice joint let us examine the middle splice joint. The only change is that all the rivets are NACA rivets. The cold working of the top row holes in the outer skin is much more (due to countersinking) than that in the inner skin at the bottom row of holes (no countersinking of the inner skin). This explains both the life enhancement as well as the cracking of the inner skin at the bottom row. The cracking of the inner skin is undesirable as it cannot be detected.

This problem has been successfully addressed by the right-most splice joint. Here the inner skin bottom row of rivet holes also has countersunk recesses. Effectively, both the outer as well as the inner skins are countersunk at the bottom row. The fatigue cracking prone area in the outer skin is the top row of rivet holes, which are countersunk. The susceptible area in the inner skin is the bottom row of rivet holes, which are also countersunk.

There is now equal chance of fatigue cracking at the top row (outer skin) and bottom row (inner skin). If crack initiation, relatively speaking, is to be delayed at the bottom row in the inner skin, the only option is to put more residual compressive stresses there by cold working i.e. to say that cold working at the bottom row has to be more than that at the top row. This is precisely done in this splice joint (right-most sketch in Fig. 8). It is worth mentioning that cracks initiating in the inner skin at the bottom row have been a recurring problem with lap splices on many aircraft.

No one would have considered a double counter sink rivet installation until Dr. Müller demonstrated it. During his Ph.D work [4] he showed that a hard squeezed double knife-edge rivet installation would always outperform a conventional protruding head rivet installation in fatigue life.

6. Concluding Remarks

- i The ageing problem in transport aircraft is primarily due to fatigue cracking of Longitudinal skin splice joints of the passenger cabin due to pressure cycling.
- ii The rivet hole fatigue cracking problem can be better understood by a proper appreciation of the role of bearing stress on the peak hoop stress in a loaded hole.
- iii Ice-box rivets with NACA installation under force control are one of the best means to enhance life very significantly.
- iv The beneficial effect of long overlaps in a lap splice on fatigue life is to be appreciated.
- v The pioneering work by Dr Muller and Dr Hart Smith reported in the paper "Making Fuselage Riveting Lap splices with 200 years of crack free life" do indicate that the problem of ageing passenger aircraft can become a thing of the past.

Acknowledgement

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References

1. LJ Hart-Smith, "Forgotten attributes of NACA rivet installations and ice-box rivets", 7th joint FAA/DoD/NASA Aging Aircraft Conference, New Orleans, Louisiana, September 8-11, 2003, Boeing paper PWDMO3-0130.
2. WG Bickley, "The Distribution of stress round a circular hole in a plate loaded through a pin in the hole", *Philosophical Transactions of the Royal Society (London),* Series A, Vol. 227, 1928, pp. 383-415.
3. RPG Muller, "Structural Modification and Life Enhancement of Fuselage Riveted Lap Joints Through Force Controlled Riveting", Research program to extend fatigue lives of riveted joints in KC135 aircraft, USAF research contract SPC98-4014^K deliverable 2.
4. RPG. Muller, "An experimental and analytical investigation on the fatigue behavior of fuselage riveted Lap joints; The significance of the rivet squeeze force, and a comparison of 2024-T3 and glare3', PhD dissertation, Delft University of Technology, Faculty of Aerospace Engineering, Structures and Materials Laboratory, Oct. 1995.
5. RPG Muller, and LJ Hart-smith, "Making fuselage riveted lap splices with 200-year crack-free fatigue lives", McDonnel Douglas paper MDC 97K0066; presented in 19th ICAF symposium, Edinburgh, Scotland, June 16-20, EMAS, England, 1997, pp.499-522.